A new absolute date from Swartkrans Cave for the oldest occurrences of *Paranthropus robustus* and Oldowan stone tools in South Africa

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ABSTRACT

The Early Pleistocene site of Swartkrans in South Africa's Cradle of Humankind World Heritage Site has been significant for our understanding of the evolution of both early *Homo* and *Paranthropus*, as well as the earliest archaeology of southern Africa. Previous attempts to improve a faunal age estimate of the earliest deposit, Member 1, had produced results obtained with uranium-lead dating (U-Pb) on flowstones and cosmogenic burial dating of quartz, which placed the entire member in the range of >1.7/1.8 Ma and <2.3 Ma. In 2014, two simple burial dates for the Lower Bank, the earliest unit within Member 1, narrowed its age to between ca. 1.8 Ma and 2.2 Ma. A new dating program using the isochron method for burial dating has established an absolute age of 2.22 ± 0.09 Ma for a large portion of the Lower Bank which can now be identified as containing the earliest Oldowan stone tools and fossils of *Paranthropus robustus* in South Africa. This date agrees within one sigma with the U-Pb age of 2.25 ± 0.08 Ma previously published for the flowstone underlying the Lower Bank and confirms a relatively rapid rate of accumulation for a large portion of the talus.

Keywords

Swartkrans[A1] Member 1; C~~c~~osmogenic burial dating; *Paranthropus*; E~~e~~arly *Homo*; Oldowan; cut-marked bone

1. Introduction

Swartkrans Cave is part of South Africa's Cradle of Humankind World Heritage Site (Fig. 1). It is renowned for its Early Pleistocene fossil and archaeological records, which chart the evolution of *Paranthropus robustus* and early *Homo*, and also provide vital information about the paleoenvironmental contexts of those processes. The site was first worked by Robert Broom and John Robinson from 1948 to 1949, followed by Robinson from 1951 to 1953, during which years many fossils were discovered, including those that provided the first evidence that *P. robustus* and early *Homo* coexisted (Broom, 1949; Broom and Robinson, 1949, 1950, 1952; Robinson, 1953; Clarke et al., 1970; Clarke and Howell, 1972; Clarke, 1977a,b). From 1965 to 1986, C.K. Brain conducted systematic research at Swartkrans, focussed especially on deciphering the site's stratigraphy and the taphonomy of its fauna, producing many more fossils in the process, as well as artifacts (e.g., Brain, 1970, 1981, 1993; Brain et al. 1988). In 2005, the Swartkrans Paleoanthropology Research Project (SPRP) began a new program of excavations (Fig. 2 and Supplementary Online Material [SOM] Fig. S1; Pickering et al., 2005, 2007, 2008, 2012, 2016; Sutton et al., 2009; Gibbon et al., 2014; Kuman et al., 2018). Here we provide a more precise date for associated Oldowan artifacts and fossils in the Lower Bank of Member 1, which has been achieved using the isochron method for cosmogenic burial dating in order to improve on two simple burial ages previously published (Gibbon et al., 2014).

Formed in a karst system, Swartkrans contains underground sedimentary infills that entered from avens that had opened to the surface over time. Member 1 is the oldest of three Early Pleistocene deposits currently recognized in the Swartkrans Formation. Brain (1993) described this member as consisting of two subunits, the Lower Bank (LB) and the Hanging Remnant (HR; Figs. 2 and 3; ~~and~~ SOM Figs. S2–S4). The HR was the source of most of the original fossils discovered by Broom and Robinson between 1948 and 1953 (Brain, 1993). The LB was discovered and named in the 1970s following continued site clearing and excavations that exposed the breccias more fully (Butzer, 1976; Brain, 1976; and see Brain [1993] for historical discussion). Its discovery demonstrated to Brain that the LB represented the first ingress of sediments, formed prior to the HR but continuous with it, and thus the separate sub-unit names are more historical than stratigraphic in significance (Brain, 1993; Gibbon et al., 2014). The LB contains thousands of macromammalian fossils, including many of *P. robustus* and some of early *Homo* (Table 1; Grine, 1988, 1989, 1993, 2005; Pickering et al., 2012), as well as stone tools (Table 2; Clark, 1993; Field, 1999; Kuman et al., 2018). Subsequently, the SPRP identified an eastern extension of the LB, designated as the Lower Bank East Extension (LBEE, and see Fig. 2), with excavations yielding lithics and fauna that are taxonomically and taphonomically consistent with the rest of the LB (Sutton et al., 2009).

Based on analyses of the HR fauna, Member 1 was originally estimated to be between 1.8 ~~Ma~~ and 1.5 Ma (Vrba, 1985), and more particularly on equid data for the whole of the member to be ca. 1.7 Ma (Churcher and Watson, 1993). These relative faunal ages were provided years ago and need updating, which is beyond the scope of this paper. They were followed by various attempts to apply other, more precise methods. First, Curnoe et al. (2001) used combined uranium series and electron spin resonance (ESR) dating on teeth from the HR and arrived at a maximum possible age of 2.11 ± 0.21 Ma. Balter et al. (2008) then attempted uranium-lead (U-Pb) dating on samples of bovid tooth enamel excavated from Member 1, but without exact provenances. That analysis produced a result of 1.83 ± 1.38 Ma, but its lack of precision is evident in the large error range. Subsequently, Pickering et al. (2011) published U-Pb dates for two flowstones, but with a stratigraphic error that was corrected in Pickering et al. (2012). As corrected, these dates bracket the entire Member 1 sequence stratigraphically (Pickering et al., 2012: Fig. 1). For the HR, two capping flowstone dates overlap in their error margins: sample SWK 9 was collected at the western end of the HR and produced an age of 1.71 ± 0.07 Ma; and sample SWK 5 was collected in the central part of the site (near the A-A' profile in Fig. 2) and yielded an age of 1.80 ± 0.005 Ma. For the speleothem underlying the LB, sample SWK 12 was collected at the western end of the site and produced a date of 2.249 ± 0.077 Ma (Pickering et al., 2011). Sample SWK 7 was collected in the central part of the site and yielded a similar age of 2.248 ± 0.052, but this flowstone formed on the northern cave wall—i.e., it does not underlie the LB as currently exposed in that location, although the HR is banked against it. Thus, based on the two overlapping dates for the HR and on the flowstone below the LB in the western part of the site, the whole of Member 1 formed more than 1.8 Ma but less than 2.25 Ma. Figure 3 shows the SPRP section through Member 1 (along the A-A' line in Figure 2). While the HR continues to the western end of the site as seen in Figure 2, the speleothems shown in Figure 3 are not yet directly dated, and so they are not given stratigraphic labels in this figure. For comparison of the A-A' section in Figure 3 with Brain's (1993) profile, see SOM Figure S2.

In an effort to provide a more precise age for the LB, Gibbon et al. (2014) measured ^{10}Be and ^{26}Al in three samples of quartz from the LB talus: a sediment sample, a chert clast collected near the sediment sample, and a quartzite manuport (SOM Fig. S5, ~~(~~bottom sample~~)~~) in curated material from the Brain LB excavation. The chert clast (SK1-Chert) and the sediment (SK1-LB) were obtained from the site by M. Sutton at the same depth (8.55 m below Brain's datum) and were sampled from the LB talus below the level where Brain's excavation ended (below square 8N/5E; see Figs. 2 and 4 for reference). The quartzite manuport from Brain's excavation was a well-provenanced cobble (SK1-M in Fig. 4), which the Oldowan occupants had collected from river gravels below the site. It was excavated from the northern (distal) side of the talus (square 7N/4E), at 5.47 m below Brain's datum.

This 0 datum is 1479.6 m above sea level, and all SPRP levels are also correlated with this datum (Fig. 3).

The depths of the 2014 samples were all sufficient to have effectively shielded them from further nuclide production following burial, allowing the decay of the inherited cosmogenic nuclides to occur. The rate of erosion affecting the depth of burial was modelled at an assumed value of 3 meters per million years, which is representative for this region (e.g., Dirks et al., 2016) and does not significantly affect the burial ages (see Gibbon et al., 2014). Results showed that the chert clast collected by Sutton did not contain enough ^{26}Al and ^{10}Be to be measured, indicating that it was not exposed at the surface and must have derived from within the cave. However, its low concentrations confirmed that postburial production was negligible. The manuport excavated by Brain produced an age of 2.19 ± 0.08 Ma, which was slightly older than the sediment sample, which dated to 1.80 ± 0.09 Ma. The two results do not overlap at three-sigma. A few potential explanations for the discrepancy in dates were considered: admixing of older sedimentary material from upslope in the talus cone during deposition, which would make the manuport age correct; reworking of the manuport within the cave, which would make the sediment age correct; and averaging the two ages, even though they disagreed by more than was statistically expected. Because these scenarios could not be resolved, further investigation was planned.

1.1. Significance of the Member 1 Lower Bank paleoanthropological assemblages

The SPRP excavations in the LB deposits adjacent to areas targeted by Brain (Fig. 2) have produced a much larger assemblage of artifacts (Table 2), and collectively the Member 1 material is assigned to the Oldowan industrial complex (Kuman et al., 2018). This is only the second substantial Oldowan lithic assemblage for this period to be documented in southern Africa. The first assemblage is 3513 pieces published for Sterkfontein (Kuman and Field, 2009), dating to 2.18 ± 0.21 Ma (Granger et al., 2015). Overall, the Swartkrans assemblage is more casually made than the one from Sterkfontein and has one of the largest proportions of bipolar flaking in the African Oldowan, including on raw materials not usually worked in this fashion (Kuman et al., 2018). These artifacts are also linked functionally to just over a dozen of the thousands of ungulate long limb bone fossils excavated from the LB. Causal connections between artifacts and fossils are in the form of cut marks and hammerstone percussion marks on the bones, created respectively by slicing and pounding tools used to butcher carcasses obtained before other competitor species consumed the best portions of those resources (Pickering et al., 2008; Pickering and Brain, 2010). No other Early Pleistocene site in southern Africa shows as robust a zooarchaeological record of early human access to large carcass resources as that from the LB of Swartkrans. Apart from Sterkfontein and Swartkrans, the only other examples in southern Africa of Oldowan tools and associated fauna are a few pieces from the nearby site of Kromdraai that have an established Oldowan age range (Kuman et al., 1997), plus about 30 artifacts dating to ca. 1.8 Ma from Wonderwerk Cave in the Northern Cape, South Africa (Chazan et al., 2008, 2012; Matmon et al., 2012). Thus, a revised age for the LB at Swartkrans is important to our understanding of the earliest archaeology of southern Africa, which is limited due to the restricted geological circumstances of its preservation.

A more precise date is also important for resolving the geological age of the earliest *P. robustus* fossils from Swartkrans, which derive from the LB (Table 1). Other early specimens of this species in South Africa include: a few fossils from Sterkfontein associated with the ~2.2 Ma Oldowan assemblage (Kuman and Clarke, 2000; Granger et al., 2015); a much larger number from Kromdraai, which are argued to be somewhat geologically older and less morphologically derived than those from Swartkrans (Braga et al., 2017; Bruxelles et al., 2017); a large number from Drimolen ca. 2 Ma (Moggi-Cecchi et al., 2010; Herries et al., 2020); and small numbers that are less well-dated from Coopers (Steininger et al., 2008; de Ruiter et al., 2009) and Gondolin (Grine et al., 2012).

2. Materials and Methods

To date the LB deposit we used the isochron cosmogenic nuclide burial dating method as described by Granger (2014), adapted from Balco and Rovey (2008). Burial dating is based on the buildup and radioactive decay of ^{26}Al (meanlife τ_{26} = 1.021 ± 0.024 Ma; Nishiizumi, 2004) and ^{10}Be (τ_{10} = 2.005 ± 0.0017 Ma; Chmeleff et al., 2010; Korschinek et al., 2010) in quartz that is exposed at the ground surface and subsequently buried. These cosmogenic radionuclides are produced primarily by secondary cosmic ray neutrons within a few meters of the ground surface, and at a much slower rate by muons at depth. By analyzing the ^{26}Al and ^{10}Be concentrations in a suite of individual clasts from the same burial depth and location, the time of deposition and the amount of postburial production can be determined from a curve that is regressed through the data (Fig. 5). We assume that each of the chert clasts enters the cave with its own inherited cosmogenic nuclide concentration determined by its exposure history at the surface, and that the clasts all share a common burial age and postburial production history dominated by production by muons at depth. In this case, the relationship between ^{26}Al and ^{10}Be is expressed in equation (1), where t is time since burial, τ_{bur} is the effective meanlife for the ^{26}Al/^{10}Be ratio ($\tau_{bur} = 1/(1/\tau_{26}-1/\tau_{10})$), R_{inh} is the ^{26}Al/^{10}Be ratio at the time of burial, N is the measured cosmogenic nuclide concentration, C is the concentration produced after burial, and the subscript indicates either ^{26}Al or ^{10}Be:

$$N_{26} = (N_{10} - C_{10})R_{inh}e^{-t/\tau bur} + C_{26} \qquad (1).$$

The initial ^{26}Al/^{10}Be ratio at the time of burial depends on the exposure history of the clast prior to burial. For clasts derived from a steadily eroding landscape, in which they were exhumed gradually to the surface and then buried in the cave, the ratio is closely approximated by equation (2), where P represents production rate at the surface (Granger, 2014):

$$R_{inh} = (P_{26}/P_{10})/(1 + N_{10}/(P_{10}\tau_{10})) \qquad (2).$$

Alternatively, for clasts that were exposed at the surface for a long time after exhumation from bedrock, the initial ^{26}Al/^{10}Be ratio is given by equation (3):

$$R_{inh} = (P_{26}/P_{10})\ (\tau_{26}/\tau_{10})(1-e^{-t/\tau 26})/(1-e^{-t/\tau 10}) \qquad (3).$$

Equations (2) and (3) serve as endmembers that bound initial $^{26}Al/^{10}Be$ concentrations. It is most often assumed that clasts are derived from a steadily-eroding landscape as described by equation (2).

The concentrations due to postburial production (i.e., C_{10} and C_{26} in equation [1]) are calculated for production by muons at depth during the time of burial. Production by muons varies with the depth of shielding. We calculated production rates of ^{26}Al and ^{10}Be at the site using the muon production rate curves of Balco (2017) for a burial depth of 7.6 meters and a density of 2.0 g/cm^3, which yielded a $^{26}Al/^{10}Be$ production rate ratio at depth of 8.7.

To accurately calculate a burial age from the isochron, we must also estimate the cosmogenic nuclide production rate at the time of burial. Production rates in the past depend on the strength of the geomagnetic field, which varies over time. Variations in production rate are strongest at low latitudes, where geomagnetic shielding is the greatest, and so are important at Swartrkans. Reconstructions of production rates over the past 2 million years (Lifton et al., 2014) indicate that production rates at the site have varied between 7 and 14 atoms ^{10}Be per gram of quartz per year, with an average of 9.8 ± 1.6 at/g/yr. Production rates beyond 2 million years ago are more poorly constrained. We use the long-term average production rate of 9.8 ± 1.6 at/g/yr, and assume that P_{26}/P_{10} at the surface is 6.8 (see SOM S1 and SOM Fig. S6 for additional information on production rates and statistical significance of isochron fits).

Eight clasts of chert and quartz were selected by DEG from archived collections from excavations conducted during May through October in 2007 (Table 3 and SOM Fig. S5). Chert was used because it has produced successful results with isochron dating at Sterkfontein (Granger et al., 2015). Of these eight clasts, six had sufficient clean quartz for dating; one was too small and another had too much native Al to make precise ^{26}Al measurements for dating. Samples were prepared by crushing the clasts to <0.5 mm and cleaning quartz by repeated partial dissolution in hot agitated 1% HF/HNO_3. Purified samples were spiked with ~0.25 mg ^9Be in a carrier solution prepared in-house from phenacite, dissolved in 5:1 HF/HNO_3, an aliquot taken for determination of [^{27}Al] by ICP-OES, and then evaporated to fumes after addition of 1 ml H_2SO_4. Aluminum and beryllium were separated by selective dissolution at pH 14 by addition of NaOH, followed by precipitation at pH 7 and ion exchange chromatography in 0.4M oxalic acid. Al and Be were precipitated as hydroxides by ammonia (Be in the presence of EDTA) and rinsed twice. Al and Be hydroxide gels were dissolved in HCl and HNO_3, respectively, dried in quartz vials, and calcined to the oxide by flame. The samples were mixed with niobium powder and packed in stainless steel holders. Isotope ratios $^{26}Al/^{27}Al$ and $^{10}Be/^{9}Be$ were measured by a~~A~~ccelerator m~~M~~ass s~~S~~pectrometry at PRIME Lab against standards KNSTD (Nishiizumi, 2004) and 07KNSTD (Nishiizumi et al., 2007).

3. Results

The cosmogenic nuclide concentrations are given in Table 3. Two possible isochrons are shown as Figure 5, calculated using equation (1) together with either equation (2) or (3) for the endmember cases of steady erosion and constant exposure.

Measured ^{26}Al and ^{10}Be concentrations have an extremely wide range. Sample #1 has a very low concentration, near the origin of the graph. Its ^{26}Al and ^{10}Be concentrations lie along the isochron and match the calculated postburial production, and so this sample's cosmogenic nuclides were almost completely produced after burial. This sample likely fell from the roof of the cave and was never exposed at the surface, similar to the chert sample of Gibbon et al. (2014). In contrast, sample #5 has extremely high concentrations, indicating a long period of exposure at the surface prior to burial. One sample (#4) lies very far above the isochron, indicating that it has a completely different burial history from the rest and is much younger. Our explanation for this sample is that it fell into the deposit from the steep eastern wall of the LB excavation, where Middle Stone Age in Member 4 (M4) overlies the LB following an erosional unconformity (Fig. 6). The sample was collected in October 2007, seven weeks after the end of the LB excavation, and was not recogniz~~s~~ed as a contaminant.

The two isochron solutions indicate somewhat different burial times. The constant exposure model yields a burial age of 2.22 ± 0.05 Ma, while the steady erosion model gives an age of 2.10 ± 0.05 Ma. Which of the two isochrons is more likely to be correct? Figure 5 shows that the steady erosion isochron calculated with equation (2) has too much curvature to fit all of the data simultaneously. It has a mean squared weighted deviation (MSWD) of 3.4, indicating that the model does not accurately describe the data ($\alpha = 0.017$). In contrast, the constant exposure isochron calculated with equation (3) has less curvature and fits the data significantly better. Its MSWD is 1.4, near the expected value of 1.0, indicating that the data are well described by the model ($\alpha = 0.24$)—see SOM S1 for explanation of the statistical test. We conclude that the assumptions in the steady erosion isochron can be rejected for this data set, and the constant exposure isochron is more likely to be correct. A third approach to the dataset would be to remove the highest point (sample #5) from the fit. In that case, the steady erosion and constant exposure curves both fit the dataset, with an age of 2.26 ± 0.06 Ma and with an MSWD of 0.6, indicating an excellent fit to the data. This age determined from the smaller dataset is indistinguishable from our preferred 'constant exposure' isochron for the full dataset, lending further support to our preferred model.

Why does this isochron follow the constant exposure instead of the steady erosion curve? One factor that may be important is that sample #5 would have had an extremely high ^{10}Be concentration of about 6.2 million at/g at the time of burial, corresponding to an unusually long effective surface exposure time of ~0.8 Ma. Its pre-burial cosmogenic nuclide concentration is among the highest ever measured from the Cradle of Humankind. For comparison, modern soil samples from near Rising Star cave have concentrations of 3–4 million at/g (Makhubela et al., 2019); the highest measured concentration for a modern sample in the area is 5.9 million at/g that was measured in a chert dike near Malapa (Dirks et al., 2016), similar to the preburial concentration in sample #5. It seems likely that sample #5 was derived from a similar vein or a resistant knob or pedestal such as crop out on hilltops in the vicinity. In that case, the cosmic ray exposure history represents two stages: the first as exhumation from the dolomite bedrock, and the second as a long period of surface exposure during which the dolomite bedrock erodes around it leaving the resistant knob proud of the surface. In this case, since most of the cosmogenic nuclides accumulate after the quartz is exposed at the surface, the 'constant exposure' model better describes the cosmogenic nuclide concentrations.

Our preferred model age of 2.22 ± 0.05 Ma is similar to but more precise than the previous burial age of Gibbon et al. (2014). It is important to note that the uncertainties above represent one standard error due to measurement and model fitting, which are appropriate for comparing with other cosmogenic nuclide burial ages. When considering an absolute age, and when comparing to results from other dating methods, additional systematic errors should be accounted for[A2]. These include uncertainties in the radioactive meanlives[A3], which add 2% uncertainty to the final age, and uncertainties in the production rate ratio. An uncertainty of 3% on the production rate ratio of 6.8 ± 0.2 adds 0.06 Ma uncertainty to the final age. Considered together, the total uncertainty on the age is 0.09 Ma, hereafter reported in parentheses. Our age of 2.22 ± 0.05(0.09[A4]) Ma lies between the bracketing U-Pb dates of Pickering et al. (2011) and is within one sigma of the age of the underlying flowstone.

4. Discussion and conclusions

Renewed efforts to resolve the age of the LB in Member 1 at Swartkrans with the isochron method have now established a cosmogenic age of 2.22 ± 0.05(0.09) Ma for the levels between 7.3–7.6 m below datum. This date agrees well with the previous simple burial age of ca. 2.19 Ma at 5.4 m below datum that was based on a quartzite manuport (Gibbon et al., 2014). The LB talus is sloped, and when re-working is not suspected, such underground deposits tend to accumulate by adding sediment to the outer surface of the talus. The 2014 date for the quartzite manuport is from the distal part of the talus and overlaps within 1 sigma with the current isochron result (from 3–4 m to the south) within a more central part of the talus, implying a relatively rapid accumulation of the sediments within these depths. Overall, 29 out of 49 hominid fossils in the LB fall within those levels

(Fig. 4), as well as the majority of Oldowan artifacts. Additionally, the isochron date is within one sigma of the U-Pb date for the underlying flowstone, which also suggests rapid accumulation for the lower part of the talus. It is possible that accumulation was initially rapid in the talus but later slowed as the entrance became choked, and so we can only say that the upper part of the LB and the HR are >1.8 Ma. However, we are working to retrieve clasts from the HR in order to date the younger part of the Member 1 talus more precisely.

For the younger date of ca. 1.8 Ma at 8.6 m depth provided in Gibbon et al. (2014), there are two possible explanations. Either the sample represents the most recent sediments to enter the talus before the aven had become fully choked, or it is contaminated with younger sediment. While both explanations are possible, the sediment sample had been collected by M. Sutton from a wall section exposed below Brain's excavation in the LB. Although Sutton reports scraping several centimeters of sediment to clean the surface before sampling, the site had remained open since 1986 following Brain's excavations. As we have seen in this work, isochron dating can detect contamination and exclude a result from the fit, but burial dating of a single sample of bulk sediment cannot detect contamination. However, a quartzite manuport (unlike the chert clasts) could only have been carried into the site from the river terrace below, and so it would be considered more reliable. This work demonstrates that the isochron method can provide a significant improvement in cosmogenic burial dating over simple burial dates. Because the age of 2.22 ± 0.05(0.09) Ma also agrees well with Pickering et al.'s (2011) U-Pb age of 2.25 ± 0.08 Ma for the M1 basal flowstone at the western end of the site, this suggests relatively rapid accumulation for a large portion of the talus. The ~1.8 Ma date for the 2014 sediment sample comes from the most distal part of the LB talus, and thus it can represent either a considerable slowing in sediment entering the cave over time, or perhaps more likely, some contamination with younger grains while the site remained open for well over two decades (between 1986 and late 2009 when the sample was collected).

Despite the limitations of cosmogenic dating used for sloped deposits, biostratigraphically derived age estimates in paleoanthropology are necessarily more imprecise than are those that are derived geochronologically. The cosmogenic results thus confirm that the LB and its fauna are older than ca. 1.8 Ma (the U-Pb dates for the capping flowstone over the entire Member 1). Fossils of *P. robustus* are distributed throughout the LB, but more than half of the LB specimens assigned to this species are also bracketed within the levels from 5.4–7.6 m dated with chert and quartzite clasts to ca. 2.2 Ma (Table 1; Fig. 4). When combined with previous cosmogenic nuclide dating results that place the age of the *P. robustus* fossils in Swartkrans Member 3 at 0.96 ± 0.09 Ma (Gibbon et al., 2014), these new results establish the current age range of this important endemic South African species as ca. 2.2–1.0 Ma. It is also interesting to note that among the numerous craniodental fossils preserved in the LB, there are only two identified as *Homo*, and these are in levels above the dated samples (Table 1). Four additional Member 1 fossils of early *Homo* retrieved by Broom and Robinson from the HR are: SK 27, a juvenile cranium now assigned to *Homo habilis* (Clarke, 2012, 2017); SK 45, a mandible fragment, and SK 847, a partial cranium, both now assigned to *Homo ergaster* (Clarke, 1994); and SK 2635, a partial palate of early *Homo* sp. (Clarke, 1977b) (see also Brain, 1981). These fossils all come from the northwest corner of the cave where only a plan of the provenances was provided by Robinson (1952). This is the pink breccia that Brain (1993) describes as Member 1, and no further detail is known stratigraphically, but they do underlie the capping flowstone dating to 1.8 Ma in that area of the site (Pickering et al., 2011).

With regard to environmental reconstruction, a large number of fossils of *Papio robinsoni* is also present in the LB as a whole (Watson, 1993), and a number of *Equus* fossils derive from the dated LB levels (Churcher and Watson, 1993). *Equus* is a xeric-adapted genus, while *Pa. robinsoni* and *P. robustus* are generally reconstructed as eurytopic generalists, although with strong trophic preferences for wooded/humid C3 environmental components (reviewed in Caley et al., 2018). The stratigraphic co-occurrence of these taxa in the LB fit well with current reconstructions of a dominant mixed or mosaic habitat for the Blaaubank River valley ca. 2.5–2.0 Ma.

Further, cut-marked and hammerstone-percussed ungulate fossils excavated from the LB provide the oldest evidence for anthropogenic involvement in the accumulation of fauna in southern

Africa (Pickering et al., 2008). The butchered bones were recovered in good association with Oldowan artifacts. The lithic assemblage from the SPRP excavations is large, consisting of 1849 pieces that include a substantial portion of small flaking debris (i.e., all artifacts <20 mm in maximum length), indicating relatively good capture of material from the surface above the cave. In an initial analysis of the Brain assemblage, Clark (1993) focused on 62 (out of 231) more meaningful artifacts, while a more in-depth study by Field (1999) later identified 298 pieces. While it is difficult to discuss the two samples due to differences in classification, an attempt at comparison is made in Table 2 by simplifying the more detailed SPRP types to conform with Field's (1999) classification. This shows that the basic types and the dominance of quartz are alike in the two assemblages, while the other raw material proportions follow in the same rank order. The smallest lithics in the Brain assemblage are under-represented, which may be due to the limited sample size or to differences in recovery protocols and/or recognition of small flaking debris. Overall, however, the LB Oldowan technology is simple, with a significant amount of raw materials casually selected from the immediate vicinity of the site, a large amount of bipolar flaking that is not limited to quartz, and few cores that are extensively flaked (see Kuman et al., 2018 for details). This contrasts with the Sterkfontein Oldowan, where better raw material was clearly selected and the cores were more heavily reduced. The two sites lie on opposite sides of the Blaaubank River and are only about 1 km apart, but Sterkfontein is slightly further from good raw materials in the gravels and more was transported to the site. While Kuman et al. (2018) explained this contrast by the difference in distance to raw materials, we continue to explore other possibilities. The new date for the LB Oldowan assemblage confirms that early tool-makers were present at both Swartkrans and Sterkfontein at a broadly similar time in prehistory. Thus far, these are the first large assemblages of such antiquity in South Africa.

In conclusion, the results discussed in this paper show that the earliest date in South Africa for *P. robustus* and Oldowan lithic artifacts is currently established by cosmogenic isochron burial dating at 2.22 ± 0.05(0.09) Ma, in the Swartkrans Member 1 Lower Bank.

Acknowledgments

Very special thanks go to Gordon Getty, Paddy Moore, and the L.S.B. Leakey Foundation for their generous support of this project through a grant awarded to TRP. Other funding for the Swartkrans Paleoanthropology Research Project (SPRP) includes: the following grants to TRP—the National Science Foundation (USA), the Palaeontological Scientific Trust (PAST, South Africa), and the Vilas Associates and Kellet Mid-Career Award Programs (University of Wisconsin-Madison); and the following grants to K.K.: PAST, the National Research Foundation (NRF, South Africa) African Origins Platform (grant number 98830), the NRF Rated Research Incentive Fund, the NRF Competitive Programme for Rated Researchers (grant number 81782), the Centre of Excellence in Palaeosciences at the University of the Witwatersrand, and the University of the Witwatersrand Research Incentive Fund. We thank Morris B. Sutton for his work on the excavation and sample collection and for his Ph.D. support from the University of the Witwatersrand, the NRF and PAST. We thank the following individuals, institutions, and companies (in alphabetical order) for their assistance with our project: African Explosives; John Cruise; Hendrick Dingiswayo; the Ditsong National Museum of Natural History (Transvaal Museum); Manuel Domínguez-Rodrigo; Charles Egeland; the Evolutionary Studies Institute, University of the Witwatersrand; A.J. Heile; Barry Jacoby; Lazarus Kgasi; Andrea Leenen; Abel Molepolle; Andrew Phaswana; the Pickering family (especially Robert for his fieldwork); Stephany Potze; the late Dusty van Rooyen; the School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand; and Francis Thackeray. This is paper no. 9 in the SPRP publication series. We thank our editor, Andrea Taylor, for her help with this paper during the review and revision process.

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Figure Legends

Figure 1. The location of Swartkrans in South Africa, and other cave sites within the Cradle of Humankind World Heritage Site, Gauteng Province. Abbreviations: GD = Gondolin; HG = Hassgat; ML = Malapa; GV = Gladysvale; DN = Drimolen; KR = Kromdraai; CP = Coopers; STK = Sterkfontein; RS = Rising Star; BF = Bolt's Farm.

Figure 2. Plan of the Member 1 deposits and excavation grid (see also SOM Fig. S1). This plan updates and revises all previously published plans in the SPRP[A5] papers. The Lower Bank (LB) consists of lightly calcified sediments and represents the earlier part of the member. The Hanging Remnant (HR) that remains today is well-calcified due to its position under the cave roof. Although the LB and HR comprise a single member formed through continuous deposition from the same entrance, the contact between them had been eroded in antiquity. During his excavations, Brain found that Member 2 had filled the eroded channel (see SOM Fig. S2). For discussion purposes, square 7N-4E in the Brain excavation is shown in this figure, but it underlies the HR. For the three squares in which the hatching symbols for the Brain and SPRP excavations overlap, the SPRP work occurred at levels below those of Brain. The Lower Bank East Extension (LBEE) is a distal part of the LB discovered underground more recently (see Sutton et al., 2009). Only the excavated squares are

shown and not the full extent of the deposit. Member 4 is a MSA colluvial deposit lacking bone. It was first noted by Brain in a miners' trench between lines 18–22E. In more recent years, MSA artifacts have also been excavated between lines 11–13E, where a bulk 2m wide along the 9–10E lines remains unexcavated and separates M4 from the LB. The capping and basal Member 1 flowstones dated by Pickering et al. (2011) were sampled from the western side of the site, along with one capping flowstone a few meters from the A-A' line in this figure.

Figure 3. Stratigraphic profile for the Lower Bank and Hanging Remnant along the A-A' line shown in Figure 2. The dashed lines indicate the sloped deposits in the LB that are now removed in both the SPRP[A6] and Brain excavations. The depth of the current isochron date from squares 6–~~-~~7E (red star) is shown in relation to the depths of the 2014 dates (white stars). The large white star represents the manuport (SK1-M from 7N/4E), with a date that overlaps with the current isochron result. The smaller star indicates the sediment sample (SK1-LB), which was retrieved from the exposed northern face of the LB below Brain's excavated square 8N/5E.

Figure 4.~~B)~~ Vertical distribution of the dated samples from the 2014 and current studies, along with depths for the hominid fossils in the Lower Bank (Table 1), artifacts ≥20 mm excavated by SPRP[A7] (only those with Total Station readings used), and artifacts from the Brain excavations as provided in Clark (1993: Fig. 5). The SPRP depths are correlated to Brain's original 0 datum point on site, which is recorded also in meters above sea level (m.a.s.l.).

Figure 5. Isochron dating results for the current study. The blue curve assumes steady erosion and does not fit the data well. The red curve assumes constant exposure prior to burial and fits the data, and is our preferred model age. Note that the lowest concentration sample lies near the intercept of the isochron and the postburial production lines, indicating that it was likely derived from inside

the cave with no prior exposure. Sample #4, interpreted as a much younger sample that fell into the excavation, is shown as an outlier near the production rate lines and is not considered in this fit.

Figure 6. Photo taken in 2006 showing the location of the Member 1 Lower Bank (M1 LB) deposit, early in the SPRP excavations. Part of the Member 1 Hanging Remnant (M1 HR) is visible as the hard deposit painted with blue stripes (paint was applied for controlled blasting to remove a dangerous section). The HR continues westwards as indicated in Figure 2. At top right, the EDM total station is standing on squares 11–13 East (before they were excavated and found to contain Middle Stone Age in the upper levels). Note the steep excavation wall between the two deposits, with a white line inserted to show the separation of M1 LB with Member 4 (M4). A clast fallen from this wall is considered to be the young outlier (sample #4). The M4 colluvial deposit with Middle Stone Age artifacts formed on an erosional surface that had truncated the HR and part of the LB, probably long after the cave roof had disappeared in that location.